

Milky Way "unveiled" to reveal a host of new galaxies

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A new high-resolution infrared mapping effort, the Two Micron All Sky Survey (2MASS), is now underway and will provide a complete census of galaxies as faint as 3 mJy (or 13.5 mag) at 2.2 μm for most of the sky, and ~ 10 mJy (or 12th mag) for regions veiled by the Milky Way. This census has already discovered nearby galaxies previously hidden behind our Galaxy, and will allow delineation of large-scale structures in the distribution of galaxies across the whole sky. Here we report the detection and discovery of new galaxies from this survey for fields incorporating the Galactic plane, and follow up H I 21-cm and optical spectroscopy observations that provide confirmation for 14 of the new 2MASS galaxies. We concentrate upon a region only $\sim 50^\circ$ from the Galactic center. These extended sources range in total brightness between 10 and 110 mJy, and have an isophotal diameter range between 20 and 120". The area-normalized detection rate is $\sim 1\text{-}2$ galaxies per deg^2 brighter than 10 mJy, roughly constant with Galactic latitude all the way down into the Galactic plane. Hence, 2MASS will increase the current census of galaxies in the zone of avoidance by up to $\sim 500\%$. Moreover, owing to its sensitivity to elliptical and other gas-poor galaxies, 2MASS will provide a key complementary data set to that of the gas-rich-sensitive H I surveys of the Milky Way Galaxy, potentially uncovering Local Group galaxies critical to the local gravity and mass density fields. We can project conservatively that $>10,000$ galaxies will be discovered in our bid to survey the entire Milky Way zone of avoidance.

Over the last two decades astronomers have learned that the local Universe exhibits a complex topology, characterized by groups and clusters of galaxies aligned along sheets and filamentary structures. The structures are often portrayed as "walls" of galaxies or "bubbles and voids," with sizes ranging from 30 to 150 million light years across^{1,2,3}. Moreover, nearby galaxies, including the Milky Way and Andromeda (M31), exhibit a bulk or peculiar flowing motion with respect to the Cosmic Background Radiation⁴ (CMB), with the signature being a large-angular scale dipole feature in the CMB. In the simplest of interpretations, the dipole is dominated (after correcting for the motion of the Sun through the Galaxy) by bulk streaming motion of galaxy clusters toward what is frequently called the "Great Attractor,"⁵ located somewhere behind the Galactic center region, ~ 4000 km/s, at $l \sim 320^\circ$, $b \sim 0$. The velocity field is complicated by infall motion of the LG toward the nearby Virgo cluster⁶, as well as a peculiar motion towards the Galactic anti-center region, the so-called "Local Velocity Anomaly"^{7,8} and the Puppis constellation^{9,10}, also located deep in the plane of the Milky Way, at $l \sim 240^\circ$, $|b| < 10$. If galaxies are the tracers of mass in the local Universe, then in order to decode these complex phenomena it is essential that we derive a complete census of galaxies and their larger cluster brethren local to the Milky Way¹¹.

This objective has been frustrated by the presence of the Galaxy itself—the Milky Way's gas, dust and stars block nearly one-half of the entire sky. Traditional surveys employing visual spectroscopic and imaging detectors have avoided the plane of the Galaxy, called the Zone of Avoidance (ZoA), and concentrated their observations on the half of the sky more than 30° from the Galactic plane. As such, not only is a significant fraction of the local Universe gravity field undefined, but the observed fraction is split

into two disconnected parts, which may lead to biases in interpreting the structure. Once it was realized that galaxies in the ZoA play an important role in deciphering the Supergalactic plane and the local Universe in general, new methods were utilized to see through the veil of the Milky Way.

The solution is to observe the ZoA at longer wavelengths that are less affected by dust attenuation. The Infrared Astronomical Satellite (IRAS) provided one of the first uniform and complete (to ~ 1 Jy) windows into the ZoA, revealing many nearby infrared-bright galaxies near or within the Milky Way^{12,13,14,15,16,17}. However, far-infrared surveys, such as the IRAS 1.2 Jy PSC and the PSCz, are ultimately limited by their poor spatial resolution and bias towards dusty galaxies (such as late-type spirals and starbursts).

One of most promising approaches to finding galaxies in the ZoA is to look for redshifted 21-cm neutral hydrogen line emission (H I). Many studies have been carried out^{18,19,10,8}, and continue with the goal to fully map the ZoA in H I, including the Dwingeloo Obscured Galaxy Survey^{20,21} and the Parkes multibeam survey²². The H I surveys have been successful at finding new galaxies in the ZoA, including a handful of very large nearby galaxies, including Dwingeloo 1, located just beyond the LG²⁰. These surveys, however, suffer from a major disadvantage: they are only sensitive to gas-rich spirals (e.g., Dwingeloo 1 and Maffei 2), which must also be nearby. For example, the Parkes ZoA survey has an rms of 15 mJy for a 26 km/s channel width. In addition to distant ($cz > 3000$ km/s) spirals, an entire class of galaxies, the ellipticals, are mostly invisible to H I surveys (e.g., Maffei 1). Elliptical galaxies not only dominate the mass density of galaxy clusters but also are the best tracers of the densest regions (the IRAS survey, e.g., was for the most part completely insensitive to large cluster galaxies,

including the core of the Coma cluster). Elliptical galaxies are key to solving the large-scale gravity and velocity fields in the local Universe. Fortunately there is a solution to these problems of incompleteness: the Two Micron All Sky Survey (hereafter, 2MASS), which complements the IRAS and H I surveys. 2MASS is sensitive to both spiral and elliptical-type galaxies as faint as 10 mJy in the ZoA.

2MASS²³ is a ground-based, all-sky imaging survey that utilizes the near-infrared atmospheric band windows at J(1.25 μ m), H(1.65 μ m) and K_s(2.17 μ m). One of the key scientific objectives of 2MASS is to study large-scale structures in the local Universe. Near-infrared surveys, and in particular 2MASS, are able to address these issues owing to their unique properties: (1) 2MASS is a highly uniform all sky survey, so a complete census is possible; (2) the mass distribution of galaxies is dominated by the older stellar population, which in turn emit most of their light in the near-infrared; (3) interstellar extinction *within* galaxies is considerably less than that observed at optical wavelengths, and similarly; (4) extinction from gas and dust in the Milky Way is greatly reduced in the near-infrared, providing a window into and through the ZoA; and (5) the spatial resolution of 2MASS allows detection and identification of the more numerous small galaxy members of clusters. The combined sensitivity and spatial resolution of 2MASS will lead to detection of over 1 million galaxies out to redshifts $>30,000$ km/s²⁴.

The first 2MASS data release (Spring 1999) includes portions of the ZoA along the Galactic Anticenter (glon $\sim 180^\circ$) and a region closer to the Galactic Center. This article presents results from the smaller denser region at: $45^\circ < l < 65^\circ$, $|b| < 20$; its location in the Milky Way is indicated in Fig. 1, part of the Sagittarius tangent arm extending from the Galactic center (GC). Even at near-infrared wavelengths the presence

of gas and dust is clearly seen near the Galactic plane, $|b| < 5^\circ$, and toward the Galactic center direction (Fig. 2). We do expect the region to be intrinsically underdense in galaxies based on the deduced velocity fields out to ~ 5000 km/s²⁷; however, we note that the northern ($|b| > 10^\circ$) part of the field has a previously identified large-scale structure²⁸, extending from 2000 - 5000 km/s (see more on this below).

The region of study ranges in stellar number density from a mere 2000 stars deg⁻² brighter than 14th mag at K_s (1.8 mJy) to an enormous 40,000 stars deg⁻² near the Galactic plane (Fig. 2). Stars typically outnumber galaxies by a factor of 100 to 10,000; hence, it is a major challenge to find galaxies amongst the stellar host. The 2MASS project employs automated star-galaxy discriminator techniques to reduce the ratio of stars to galaxies to a more manageable 2:1 or 1:1 ratio²⁴. It is then a straightforward process to cull out the remaining non-extended sources (such as triple stars) using visual examination of images. We also compared our source lists with astronomical databases to identify previously catalogued objects.

The major limitation endured by 2MASS in the ZoA is "confusion" noise from stars. The confusion noise becomes appreciable within an area $\pm 5^\circ$ of the Galactic plane. The end result is a loss of sensitivity as the surface density of stars increases exponentially, and a profusion of multiple star groupings (double and triple stars) that can mimic galaxies under relatively rare circumstances and be picked up by the automated extended source detection and extraction routines. A different sort of problem arises from the fact that galaxies and Galactic extended sources are sometimes difficult to discriminate from each other based on their morphology and colors. H II regions are found predominantly at galactic latitudes $< 3^\circ$. To firmly establish the extra-galactic

nature of 2MASS extended sources deep in the ZoA necessitates near-infrared or 21-cm (H I) spectroscopy to measure the cosmological redshifts.

Some $\sim 200 \text{ deg}^2$ were surveyed by 2MASS in the specified region (see Fig. 3), comprising over 1000 verified extended sources brighter than 13.5 at K_s (2.8 mJy), and >200 sources brighter than 12.1 at K_s (10 mJy) corresponding to the flux limits deep in the galactic plane (confusion noise limited). A small fraction of the sources, $\sim 15\text{-}20\%$, are previously catalogued sources. We discovered nearly 130 new extended sources brighter than 10 mJy deep in the ZoA at $|b| < 10^\circ$, dropping to 92 at $|b| < 7^\circ$ and ~ 48 at $|b| < 3^\circ$. Normalizing by the areal coverage gives a detection rate of ~ 1 to 2 per deg^2 , independent of galactic latitude. Follow up optical ($0.38 - 0.75 \mu\text{m}$) spectroscopy of 8 sources with $|b| > 8$ (i.e., less affected by dust obscuration) were acquired using the F.L. Whipple Observatory Tillinghast reflector. The measured redshift uncertainties range between 20 and 40 km/s. For the more obscured regions, H I observations were obtained during the period of May 8 -11, 1999, for seven galaxy candidates using the Arecibo 305-m radio telescope with the new Gregorian reflector system, achieving 21 km/s resolution after smoothing with 0.9 mJy rms. The resultant heliocentric redshifts and line widths for the sources are given in Table 1. The HI-observation galaxies were selected based on their morphology: spiral galaxy profiles and surface brightness that would suggest gas-rich content. One galaxy candidate did not have an H I detection, which means either the source is (1) a gas-poor early-type spiral or elliptical galaxy, (2) a Galactic extended source containing little neutral atomic hydrogen, or (3) outside the range of redshifts $0 < cz < 10,000 \text{ km/s}$ surveyed.

We conclude that the extended source sample is dominated by background galaxies, except at the lowest galactic latitudes ($|b| < 3^\circ$), where nebulae in the Milky Way are comparable in numbers to real galaxies. Consequently, the extended source detection rate serves as an upper limit for the *galaxy* detection rate. Examples of typical extended sources found in this ZoA region are shown in Fig. 4, and some of their basic parameters are given in Table 1. Note that this sample represents only about 10% of the total in Fig. 3. At the grey-edge of the ZoA (e.g., upper panel, Fig. 4), many ($>25\%$) 2MASS extended sources are previously catalogued galaxies. But as the source density and visual extinction increase (see bottom panels, Fig. 4), only a few (mostly IRAS) catalogued objects remain—precisely where 2MASS will greatly extend our current knowledge of the ZoA. Finally, we note that many of the galaxies in Table 1 have redshifts between 5000 to 8000 km/s, which is where we would expect an extension of the large-scale "Great Wall"¹ to be located *if* the western extent²⁸ were beginning to close off as another "bubble" feature. A more complete redshift census of galaxies in this field is required to substantiate this hypothesis.

The 2MASS extended sources have intrinsically red colors ($J-K_s > 1$) which make them stand out compared to the foreground stellar population. In the ZoA, interstellar reddening adds to the already red colors, although stellar light contamination from the foreground population will slightly offset the galaxy colors toward the blue (the field of #10 & #23 in Fig. 4 are contaminated in particular by foreground "blue" stars). The 2MASS processing attempts to automatically remove as much foreground contaminant light as possible by identifying point sources and subtracting their light profiles²⁴. Several large, $>90''$ in diameter, galaxies are newly discovered. One is a very bright

early-type spiral, $K \sim 9^{\text{th}}$ mag (at least 15% of the flux is cut-off due to the image edge) and $70''$ in size (#13, Fig. 4), found at a galactic latitude $+6.9^\circ$, see Table 1. Likewise, several other new H I-confirmed galaxies are located deep in the ZoA.

We highlight one of these galaxies in Fig. 5. Here we compare the 2MASS infrared vs. the Digitized Sky Survey²⁹ optical images to demonstrate the effect of extinction on the surface brightness of the background galaxy. The galaxy (#26, Fig. 4) is located at a Galactic latitude of 2.6° . It has a K_s flux of 10.30 mag (53 mJy), and a very red J- K_s color of 1.51 mag. Morphologically the galaxy appears to be an \sim Sb or later-type spiral, from which we would expect an intrinsic color of between 0.9 and 1.1. The reddening is therefore approximately 0.4 to 0.6 mag in J- K_s , corresponding to a visual extinction of 3 to 4 mag (i.e., the visual light is attenuated by a factor of 15 to 40). We may compare this rough empirical estimate with what is deduced from coarse-resolution H I, IRAS and COBE surveys, all of which trace the dust extinction. The H I column density (obtained from the Dwinglo H I survey²⁶) along the line of sight to the galaxy is $0.686 \times 10^{22} \text{ cm}^{-2}$, translating to a visual extinction of ~ 3.6 mag. At considerably better spatial resolution, IRAS and COBE/DIRBE far-infrared maps indicate that the visual extinction is slightly higher, 4.9 mags. The far-infrared derived extinction implies that, based on its infrared morphology, the galaxy is even bluer and later type than previously estimated. Correcting for extinction, the true K_s -band flux of the galaxy is 9.6 - 9.9 mag (75 - 100 mJy), which suggests that it is located relatively nearby (< 3000 km/s) assuming an L^* luminosity. The proximity of this galaxy is confirmed by a strong H I detection, top panel Fig. 5 (also see Table 1) indicating that the galaxy is a nearby spiral at 2722 km/s. Additionally, we have obtained deep K-band ($2.2 \mu\text{m}$) observations

with the Palomar 200" telescope to more accurately gauge the morphology and extent of the galaxy. These data achieve a sensitivity limit of $21.6 \text{ mag/arcsec}^2$ in surface brightness, or about 10 times fainter than 2MASS. The deep K-band images corroborate the 2MASS finding of a late-type spiral galaxy with a highly inclined orientation, extending some $70''$ in total extent down to $\sim 21 \text{ mag/arcsec}^2$.

These data demonstrate the versatile power of the 2MASS survey: the nature of the extended source can be accurately deduced from the near-infrared data in conjunction with extinction data. Follow up redshift observations are still necessary, but likely targets are easily identified with 2MASS because it is finding real galaxies in the ZoA at a rate much higher than past surveys.

Given the detection rate in this region of the Milky Way, we estimate the total number of galaxies that 2MASS will find in the entire ZoA. Integrating the rates for $|\text{bl}| < 10$ gives between 7000 and 14000 galaxies brighter than 10 mJy at K_s . This estimate is conservative since the region studied in this work has a much higher stellar density (translating to higher confusion noise and lower sensitivity) than in the Galactic anti-center region. Moreover, the region studied here is likely to be underdense in galaxies in comparison to the anti-center/Supercluster fields and the region encompassing the Great Attractor. Therefore it is more likely that 2MASS will uncover more than 20,000 to 30,000 galaxies deep in the ZoA. We expect many of these sources to be in common with ongoing H I surveys, although it is worth noting that none of the Arecibo H I detections in the present sample is sufficiently strong that they would have been detected in these H I surveys. Hence, we expect at least half (and probably considerably more) to be detected only by 2MASS. The 2MASS census of galaxies in the ZoA will therefore be 3

to 5 times larger than the current IRAS and H I samples, providing the necessary information toward identification of galaxy clusters veiled by the Milky Way. These clusters in turn will help establish the large-scale structures extending into the ZoA and probe the mass density of the Hydra-Centaurus-Pavo-Indus-Telescopium wall of galaxies. By relating the observed infall velocity to the distribution of matter, we can estimate the mean mass density of the Universe.

Finally, it is still possible that a large previously undetected local group galaxy will be uncovered by 2MASS or the H I surveys in upcoming years as these surveys reach their peak in productivity. A galaxy the size of the Milky Way or Andromeda will have enough mass to play a significant role in the gravity field of the LG, conceivably the source of complex and puzzling peculiar velocities observed in the LG and other nearby groups. It is more likely that smaller LG galaxies will be discovered, a prospect that would also be important to understanding the Local Group of galaxies. What we can say with confidence is that the zone of avoidance is now a zone of discovery.

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TABLE 1 Parameters of a sample of 2MASS extended sources in the ZoA

index	ra	dec	b	K _s	J-K _s	cz	W50	M _{HI}	Catalog
1	306.60947	15.01784	-13.2	10.66	1.09	8506			CGCG
2	309.92590	13.96138	-16.4	11.30	1.18	6299			CGCG
3	311.28094	13.39664	-17.8	11.54	1.19	8393			2MASS
4	311.23340	13.36182	-17.8	11.92	0.96	19321			2MASS
5	310.60028	13.73427	-17.1	12.06	1.10				2MASS
6	279.99750	23.87788	13.0	12.19	0.89	4668 ²⁸			CGCG
7	281.98737	22.94255	11.0	10.05	0.96	4359 ³⁰			UGC
8	282.90720	23.63469	10.5	10.20	1.12	4575 ¹⁶	137 ¹⁶	2.8 ¹⁶	UGC
9	282.01831	19.03255	9.3	10.41	1.12	5156			2MASS
10	282.32553	22.42205	10.5	11.72	1.13	?			2MASS
11	300.34976	12.68106	-9.3	12.00	1.28				2MASS
12	282.27026	22.33636	10.5	12.13	1.18	25405			2MASS
13	284.89490	19.10603	6.9	9.24	?	8554	189	8.2	2MASS
14	284.94644	18.83051	6.7	9.84	1.22	4689 ¹⁶	548 ¹⁶	6.3 ¹⁶	IRAS
15	284.90173	19.42743	7.0	10.32	1.12	3117 ³¹	264 ³¹	5.8 ³¹	UGC
16	299.93231	14.76543	-7.8	10.91	0.94	4430 ¹⁵			CGCG
17	284.23566	17.96214	6.9	11.32	0.90	4799	283	0.67	2MASS
18	281.45422	14.09969	7.6	11.80	1.16	8519	219	2.2	2MASS
19	297.61945	18.37758	-4.1	10.39	1.38	3975 ¹⁶	366 ¹⁶	3.9 ¹⁶	IRAS
20	284.82419	13.27716	4.3	10.50	1.37	7309 ³²			IRAS
21	295.04672	29.28221	3.4	10.73	1.13				2MASS
22	285.15134	18.40906	6.3	11.51	1.33	7073	388	3.0	2MASS
23	284.16830	13.20656	4.8	11.88	1.30				2MASS
24	288.23611	22.56506	5.6	12.12	1.42	8979			2MASS
25	295.95224	23.48859	-0.2	10.29	2.65				IRAS
26	286.57559	12.93881	2.6	10.30	1.51	2722	288	1.3	IRAS
27	288.85568	16.92184	2.5	10.91	2.13	6551	487	3.8	IRAS
28	294.38489	23.74393	1.2	11.01	2.12				2MASS
29	294.66907	21.82365	0.0	11.40	3.64				IRAS
30	291.54456	21.98348	2.6	11.99	1.97				2MASS

Table notes: index is the order of appearance in Fig. 4; ra & dec are the equatorial coordinates (J2000); b is the galactic latitude coordinate; 2MASS K_s mag and J-K_s color; cz is the heliocentric redshift in km s⁻¹; W50 is the 50% H I velocity widths in km s⁻¹; atomic hydrogen mass, M_{HI}, given in units of 10⁹ M_o, assuming H₀ = 75 km/s/Mpc. For source #10, spectroscopic measurements indicate that a foreground star is located directly in front of the galaxy core.

Figure Legend

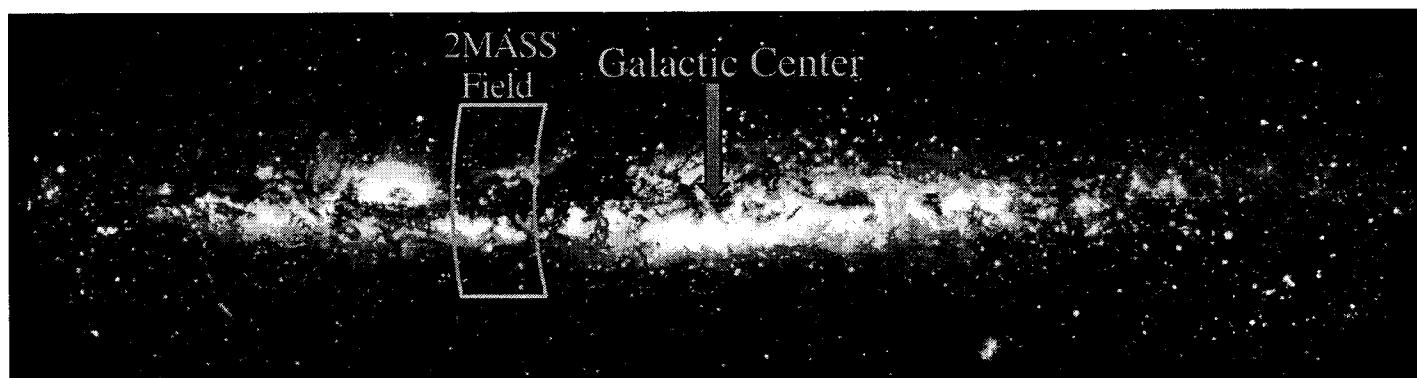
Figure 1 The visible Milky Way Galaxy. Home to some 400 thousand-million stars, including the Sun, interstellar gas and dust, nearly all of which are confined to the "disk" or Plane of the Galaxy. The Galactic plane, depicted here in a scientifically-accurate drawing from the Lund Observatory²⁵ as seen at visible wavelengths, is characterized by patchy and thick dust lanes crossing a very high surface density "disk" of stars. This region fills nearly a quarter of the observable sky, in effect a giant curtain or veil to the Universe beyond the Milky Way. 2MASS will survey the entire sky, revealing both deeply embedded star formation regions and galaxies located beyond the Milky Way. The region of the plane relevant to this work is indicated with a green box, located between 45° and 62° in longitude from the Galactic center, in the Sagittarius Arm Tangent.

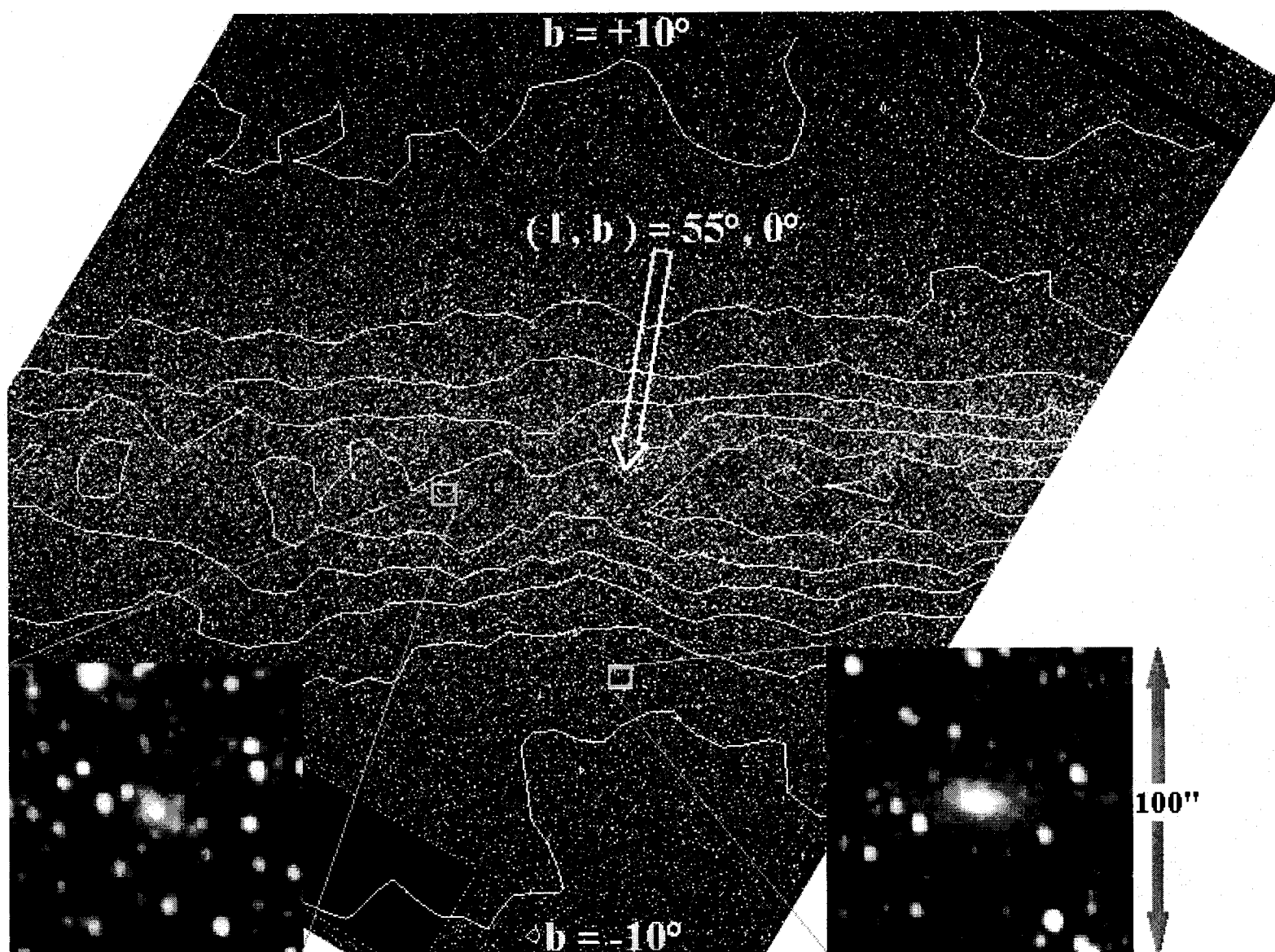
Figure 2 2MASS view of the Milky Way near $(l, b) = 55^\circ, 0^\circ$, spanning some 500 deg^2 . The RGB color composite images are derived from assigning the color blue to the J band ($1.2 \mu\text{m}$), green to the H band ($1.6 \mu\text{m}$) and red to the K_s band ($2.2 \mu\text{m}$). Note the effects of dust-extinction reddening near $|b| = 0$ and in the direction of the Galactic center (right side of figure). The extinction roughly tracks to the atomic hydrogen column density, represented by the white contours²⁶, which range from $1.8 - 14 \times 10^{21} \text{ cm}^{-2}$ (in steps of $2.1 \times 10^{21} \text{ cm}^{-2}$). Inset images represent a galaxy (lower right) and a probable H II region (lower left) that illustrate the ability of 2MASS to peer into and through the Milky Way. Missing image data appear as black strips.

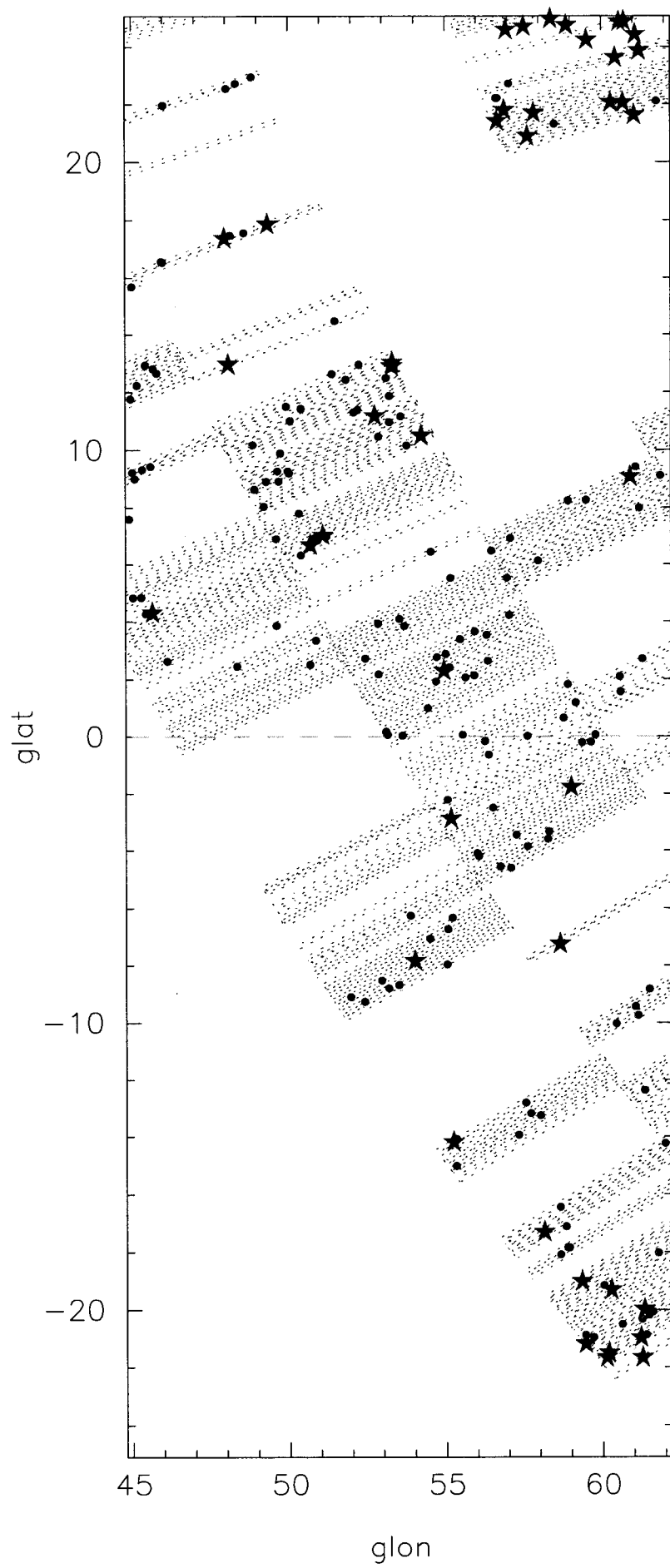
Figure 3 The distribution in galactic coordinates of ~ 200 galaxies and extended sources in the ZoA brighter than $K = 12.1$ mag (10 mJy). The dashed (red) rectangles demark swaths of sky fully covered by high-quality (i.e., photometric) data from the 2MASS survey. The total area covered is ~ 200 deg². Filled (blue) star-symbols denote previously-cataloged galaxies, 40 in total, and filled (black) circles denote newly-catalogued extended objects.

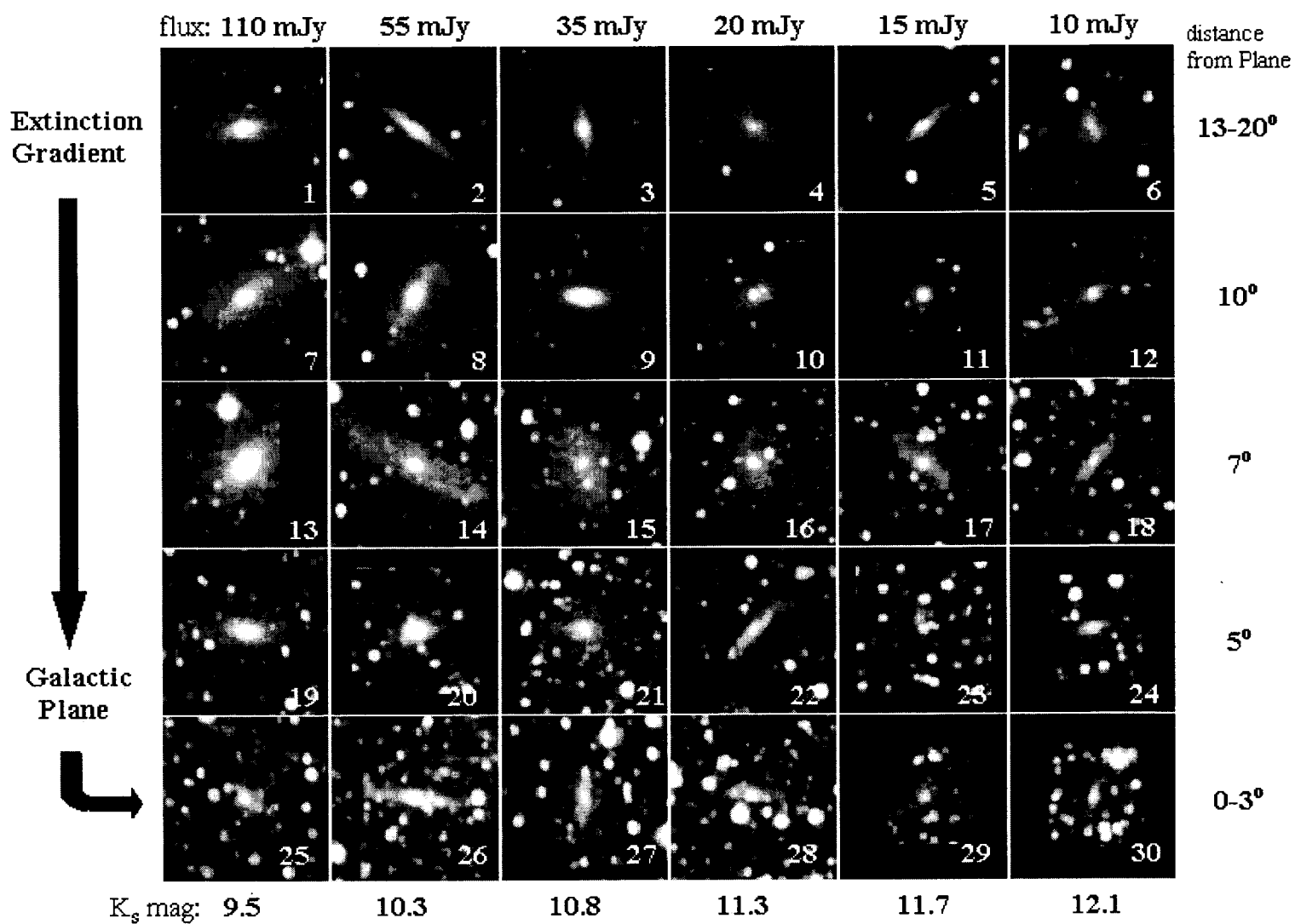
Figure 4 Sample of galaxies and extended sources seen through the Milky Way at the 2MASS near-infrared bands. Each image is $90''$ in angular size. The RGB color-composite images are ordered in decreasing (reading left to right) total integrated flux ranging from 110 mJy to 10 mJy (corresponding to a K_s magnitude range from 9.5 to 12.1), and in increasing stellar surface density or dust obscuration (reading top to bottom), ranging in latitude $|b|$ from 20 to 0 degrees. See Table 1 for measured parameters.

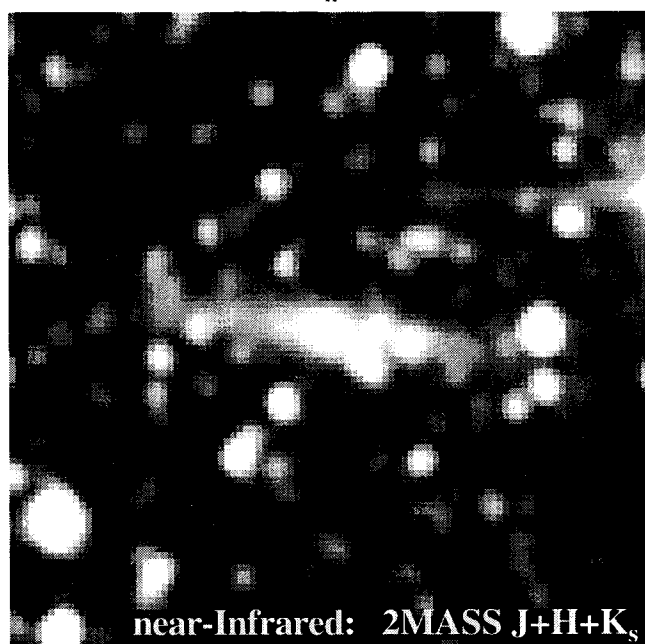
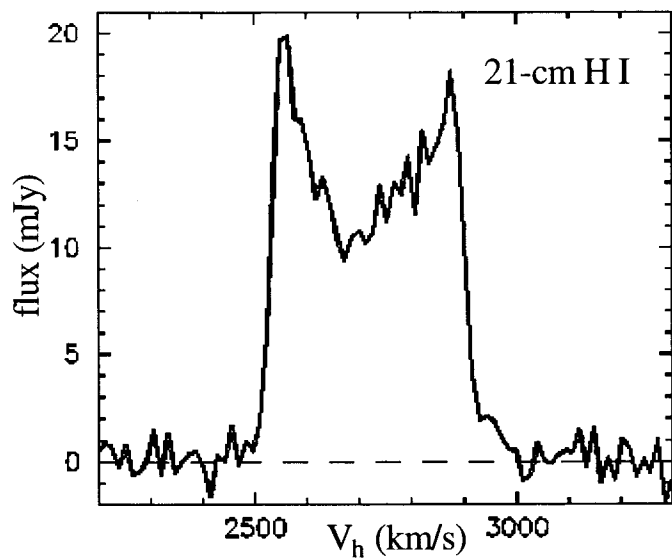
Figure 5 Newly confirmed galaxy deep in the Galactic plane, 46° longitude, $+2.6^\circ$ latitude (2MASSXJ1906181+125619 == IRAS 19039+1251; see TABLE 1). 21-cm H I observations verify the extra-galactic nature of the object (top panel), showing the classic double-peak profile of a spiral. At near-infrared wavelengths (middle panel), the galaxy appears to be a Sb or later-type spiral highly inclined to our line of sight. For comparison, the bottom panel shows the same region as seen at visual wavelengths, from the Digitized Sky Survey²⁹, showing the galaxy to be mostly invisible due to the dust obscuration from the foreground Milky Way.











100"

